Pion Production and Fragmentation of Nuclei in High Energy Nucleus-Nucleus Collisions

by

Anders Oskarsson

Lund 1983

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DOKUMENTTITEL OCH UNDERTITEL Pion production and fragmentation of nuclei in high energy nucleus-nucleus collisions.

SAMMANFATTNING In collisions between nuclei at high energies one can study the behaviour of nuclear matter under extreme conditions, regarding nuclear density and temperature. The Bevalac and the CERN SC beams have been used and nuclear emulsion and scintillation telescopes have measured the reaction products. Collisions at 50A-200A MeV and at 2A GeV have been investigated.
Proton spectra from ^{12}C induced reactions at 85A MeV have been taken for different targets. Energetic protons at large angles can be assumed to be emitted from a source moving with half the beam velocity and a temperature between 13 and 17 MeV, depending on the target. This source consists of equal contributions from the projectile and target. In collisions between nuclei, pions can be produced below 290A MeV due to the internal Fermi motion of the nucleons. (290 MeV is the threshold for free nucleon-nucleon collisions). Subthreshold pion production has been studied for ^{12}C induced reactions at 85A and 75A MeV. The cross-sections are consistent with a quasi-free nucleon-nucleon scattering picture, involving Fermi motion, Pauli blocking and pion reabsorption. Details in the shape of the spectra for asymmetric reactions are difficult to understand without very strong absorption of pions. ^{16}O induced reactions in emulsion have been studied at 75A, 175A and 2000A MeV. It is shown that the excitation of the parts of the nuclei cont.

NYCKELORD Nuclei, collisions, high energy, protons, pions, subthreshold, spectator-participant, fragmentation, momentum-transfer, correlations

DOKUMENTTITEL OCH UNDERTITEL – SVENSK ÖVERSÄTTNING AV UTLÄNDSK ORIGINALTITEL
Pionproduktion och fragmentation av kärnor i högenergetiska kärn-kärn kollisioner.

TILLÄMPNINGSOMRÅDE Grundläggande kartläggning av tungjonskollisioner vid intermediära och höga energier. Separerar speciellt perifera och centrala kollisioner. Spektra lämpliga för jämförelser med modellräkningar speciellt nucleon och pion emission. Redovisar erfarenheter av detektion i 4π geometri.

NYCKELORD 4π detektorer, differentiella tvärsnitt, protoner, pioner, tungjonskollisioner

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which are not overlapping (the spectators) increases with the beam energy. There must exist a mechanism which transports energy from the overlapping parts to the spectators and this mechanism is more efficient at higher energies although the interaction time is shorter. The ^{16}O projectile frequently breaks up into multiple He fragments. These events are associated with large impact parameters. It is demonstrated that a convenient measure of the impact parameter could be to count the number of charges carried away by multiply charged projectile fragments.

Central collisions with Ag,Br target at 50A-110A MeV have been analysed separately. It is shown that the momentum transfer to the target nucleus is limited to a value considerably lower than the full momentum transfer in a fusion reaction. Events are observed where there are numerous fragments with $3 \leq Z \leq 8$. These multifragmentation events cannot be understood in a thermal approach.

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Anders Oskarsson
Hallands Nation

Denna doktorsavhandling vid Lunds Universitets Matematisk-naturvetenskapliga fakultet kommer att försvaras vid offentlig disputation den 29 april 1983 i föreläsningssal B vid Fysiska Institutionen i Lund. Disputationen äger rum i stillhet.

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Pion Production and Fragmentation of Nuclei in High Energy Nucleus-Nucleus Collisions

by

Anders Oskarsson

Department of Physics
University of Lund
Sölvegatan 14
S-223 62 LUND.

Preface.

This thesis presents the results of experimental research at the Department of Cosmic and Subatomic Physics, University of Lund, Sweden. The research performed from 1977 to 1982 concerns high energy nuclear collisions. The body of the presentation is made up of 7 publications all of which are published in widely spread international scientific journals

I Pion and proton multiplicities in heavy ion reactions at 75 - 200 MeV/nucleon.
Phys. Rev. Lett. 40, 289 (1978).

II Properties of participants and spectators in non-peripheral Fe-induced reactions at 1.7A GeV.
Phys. Lett. 82B, 216 (1979).

III The breakup of ^{16}O into He an event-by-event study of nucleus - nucleus collisions at 75, 175 and 2000 MeV/A.
Nucl. Phys. A381, 544 (1982).

IV Correlations between projectile and target break-up in intermediate and high energy heavy ion collisions.
Nucl. Phys. A392, 474 (1983).

V The disintegration of nuclei in violent heavy ion interactions at 55A MeV - 110A MeV.
Z. Physik A307, 293 (1982).

VI Proton emission in 58A and 86A MeV ^{12}C-induced heavy-ion reactions.
Phys. Lett. 102B, 121 (1981).

VII Sub-threshold pion production in heavy-ion collisions at 85A MeV.
Phys. Rev. Lett. 48, 732 (1982).

The results have also been presented at the following international conferences in heavy ion physics:

The 15th International Cosmic Ray Conference, Plovdiv, Bulgaria (1977).

The Symposium on Relativistic Heavy Ion Research, Darmstadt, West-Germany (1978).

The Symposium on Nuclear Physics in Heavy Ion Collisions between 10A and 300A MeV Copenhagen Denmark (1979).

The 3rd Nordic Meeting on High Energy Reactions in Nuclei, Geilo, Norway (1979)*.

The 5th High Energy Heavy Ion Study, Berkeley, USA (1981)*.

The 4th Bergen Workshop in Nuclear Physics, Bergen, Norway (1982).

Conference Internationale sur quelques aspects des Reactions entre Ions Lourds, Saclay, France (1982)*.

The Conference on Nucleus-Nucleus Collisions and Nuclear Excitations, Dubna, USSR (1982).

The Nordic Meeting on Nuclear Physics, Fuglsö, Denmark (1982).

The Heavy Ion Conference, Michigan State University, USA (1982).

The Seminar on High Energy Physics with Emulsion, Cairo, Egypt (1982)

The asterisks mark the presentations made by myself.

The introduction offers a short description of the evolution of the field of intermediate and high energy heavy ion reactions during the years when these experiments were done. My ambition is not to give a summary of the whole field, but merely to shed light on the circumstances around each experiment at the time it was performed. Which were the questions raised and which experimental possibilities were available to answer them?

The field has experienced a quick change during these years. The need for rapid publication has given many of the papers a letter character. They contain only little description of the experimental equipment and the problems faced in the use of it. Thus section 2

discusses the experimental techniques, the accelerators, the detectors and the data analysis.

In section 3 each paper is presented and commented. Cross-references between the papers are made when the same physical effects show up in different observables. In two cases some data obtained after publication are included to complete the picture.

Section 4 gives some personal reflections on the field including some (self-)criticism. A few comments are made on future experiments that could be done with the available technique and which would be natural extensions of the experiments in this thesis.

In the last section the papers appear exactly as they were published.

This is a good opportunity to thank all the people without whose help this thesis would never have been completed. Those involved in the specific projects have already been acknowledged in the papers and I can only repeat my sincere gratitude to them.

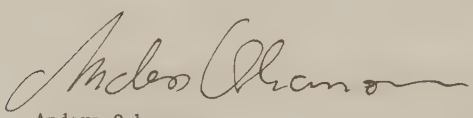
To my collaborators and cowriters, all of them experienced physicists in the field: All I have learned, you have taught me. Thank you for that. It is quite a lot.

To the supervisors in the daily work: Ingvar Otterlund who brought me into this and whose enthusiasm is the driving force behind any new plot, Bo Jakobsson who can do anything on his Texas, Rune Kullberg busy-wait, but he taught me emulsions, Hans Ryde whose encouragement speeded up my Ph D-studies. I thank you for your stimulating guidance and your clever application for money.

The sources of financial support, mainly the Swedish Natural Science Research Council (NFR), are gratefully acknowledged. Money from "Kungliga Fysiografiska Sällskapet, Lund" brought me around the world for conferences and personal meetings. This is an essential ingredient of the research in this dynamic field.

Finally to my friends (to which also the people mentioned above belong) at the Department of Cosmic and Subatomic Physics. When you have such friends you need no enemies.

Lund February 1983.



Anders Oskarsson.

1. Introduction.

The beginning of systematic studies of collisions between nuclei at high energies was in the early 1970's when the Bevalac was modified to accelerate heavy ions. Before that, only experiments with cosmic ray projectiles had been done, mainly with nuclear emulsion.

In the beginning, light nuclei e.g. ^{16}O at 2.1A GeV were accelerated The reaction probability was found to be well described by the geometrical cross-section. The importance of the collision geometry at a certain impact parameter was formulated in the spectator-participant picture. This is still the basic building-stone for most models proposed for the reaction mechanism. It states that only the nucleons located in the volumes of the nuclei that geometrically overlap, participate in the violent stage of the reaction, whatever that is. Non-overlapping nucleons are basically unaffected by the collision.

In its most straight-forward form the geometrical overlap is defined by the hard sphere radii of the nuclei. These are assumed to pass each other along straight line trajectories and make clean cuts through each other during passage. The collision time is assumed to be short enough to prohibit communication between the participant and the spectators.

The description of the spectator fragmentation as the sudden breakup of a Fermi-gas of nucleons has successfully explained the systematics in the measured momentum distributions of the emitted projectile-like fragments in peripheral collisions /1/.

For the violent breakup of the participant many different suggestions have been made. Depending on the mean free path (λ) of nucleons in nuclear matter compared to the typical distances (R) that a nucleon travels through a nucleus, quite opposing situations might occur. If $\lambda \gg R$ a projectile nucleon will scatter only a few times on target nucleons, and the outcoming particles will have the characteristics of quasi-free nucleon-nucleon scattering. A subsequent cascading might occur if the nuclei are large. On the other hand if $\lambda \ll R$, the incoming kinetic energy is distributed through many successive collisions among many nucleons in the participant. The breakup is then ruled by statistical arguments in thermal models like fireball- firestreak- /2/ or hot spot models /3/. If the nucleons cannot be treated as independent the behaviour of the bulk nuclear matter could be described as a collective hydrodynamical motion.

The situation is that none of these conditions is unambiguously fulfilled. Fair agreement with inclusive nucleon spectra can be achieved with any of the mentioned models, at least their shapes are reproduced. Calculated absolute levels of inclusive spectra are normally correct to within a factor of two.

Inclusive measurements are evidently not decisive enough to find the signatures of the reaction mechanism. One has to proceed with exclusive experiments measuring as many of the reaction products as possible in each event. Some of the experiments in this work are of this type (papers II, III, IV, V). Nuclear emulsion detectors are used to register all particles emitted in the event. By considering the charged particle multiplicity, peripheral collisions can be separated from central ones. It is also possible to determine which

particles come from the projectile spectator and which come from the target spectator. The analysis in papers II, III, IV and V is concentrated on studies of the breakup properties of the spectators in peripheral and central collisions separately. The clean cut spectator-participant model is tested and is found to work only for the most peripheral collisions.

The production of pions in nuclear collisions is confined to the participant volume where the energy density is the largest. Are pions simply created in the individual collisions between projectile and target nucleons (NN collisions) or are there any collective channels in operation? Of course, there is a contribution from independent NN-collisions and the problem is to resolve a possible collective component from this. For free nucleons, 290 MeV is the threshold energy for the reaction $NN \rightarrow NN\pi^{+-}$. In nuclei however, the help from the internal Fermi-momenta of the two nucleons allows this reaction down to a few tens of MeV per nucleon, but with a strongly reduced cross-section. Searching for collective effects it is natural to investigate this "sub-threshold" region.

In 1977 an experiment at the Bevalac reported an enormous cross-section ($\sim$ 3b) for charged pions below 290A MeV. This result was immediately denied by two other experiments using the emulsion technique. One of them is presented in paper I of this thesis.

The change of the CERN Synchrocyclotron to heavy ions (^{12}C) in 1980 offered a high intensity beam in the intermediate energy range. Quantitative measurements of pion production are thus feasible down to below 100A MeV The experiment reported in paper VII studies production of π^+ at 85A and 75A MeV. The experiment confirms the

emulsion investigation with cross-sections in the μb range, a level which could be understood in the nucleon-nucleon scattering picture.

Great interest in the field of intermediate energy(20A - 200A MeV) heavy ion collisions has arisen during the past years. Today, 1983, many accelerators operating in this domain are starting up and many activities are foreseen in the years to come. The first generation experiments already done at CERN and Berkeley have revealed great similarities with reactions at relativistic energies

Our program at the CERN SC has, besides the π^+ measurements already mentioned, also involved studies of elastic scattering /4/, the fragmentation of the projectile /5/ and measurements of inclusive high energy light particle spectra The latter investigation is reported in paper VI.

Event by event studies at intermediate energies have so far mostly been made in nuclear emulsion. Papers III, IV, V contain information on the topology of individual events. Paper V concentrates on central collisions and the fragmentation of the heavy target nuclei. The momentum transfer to the target residue is determined. Papers III and IV contain comparative investigations of collisions at intermediate and relativistic energies.

2. The experimental tools.

The experiments on which this thesis is based have been performed at two accelerators, the CERN Synchrocyclotron (papers VI and VII) and the Bevalac in Berkeley (the emulsion works papers I-V) which together with the Synchrophasotron at Dubna have been the only heavy ion accelerators operating at intermediate and relativistic energies.

2.1 The nuclear emulsion experiments.

Together with the streamer chamber experiments at Berkeley and Dubna nuclear emulsion has been the most important 4π detector during the first decade of accelerator experiments. The use of the nuclear emulsion technique in the studies of high energy nuclear collisions has its roots in the cosmic ray studies. Emulsions provide a simple and cheap 4π-detector with a quite unambiguous spatial and angular resolution, ideal for the very large particle multiplicities obtained at the highest energies. It has some obvious experimental drawbacks, the difficulty to determine the target nucleus and the tedious collection of the data. Carefully used the emulsion technique can however, extract quite unique information where other techniques would require very complicated counter telescope arrays.

The emulsion exposures have been performed at the Bevalac in the 250A MeV and 2.1A GeV ^{16}O beams and in the 1.9A GeV ^{56}Fe beam The exposures were always done with the beam parallel to the emulsion surface to simplify the observation of the collision stars. The stacks were irradiated with a defocused beam in order to produce a uniform flux of beam particles into the stack. Very little beam time is needed since the maximum number of primary tracks allowed with

maintained transparency of the emulsions is ~10^4 per cm^2. The number of nuclei hitting the stack is counted directly with plastic scintillators placed in the beam.

By proper choice of the sensitivity of the emulsions and the processing parameters, a desired blackness of a track (blob density) at a certain ionization can be achieved. About 15 blobs per 100μm for a singly charged particle at minimum ionization is convenient since it allows both observation of shower particles as well as acceptable charge identification of projectile fragments and slow target particles (papers I - V).

Scanning for collisions is done under microscope, normally at 250x magnification. The scanning efficiency is checked by double scanning both by different scanners and at larger magnification. To be accepted as an interaction one of the interacting nuclei must emit at least one charged particle. Consequently, elastic scattering events are never included. More than 90% of the total reaction cross-section is found in the scanning procedure.

At relativistic energies the particles emitted from the projectile and from the participant have ranges too long to be stopped in an emulsion stack. Thus no energy determination can be made. Charge identification is only possible for the obvious projectile spectator fragments, if one assumes that they have the velocity of the projectile (a good enough approximation at these energies). The analysis of collisions at ~2A GeV is based on the commonly used n_s, n_g, n_b multiplicities (defined in paper II), and angle measurements. The emission angle is, for particles emitted from a system in motion, a quite informative parameter. It involves the combined effects of

the source velocity as well as the momentum of the particle in the source system. These properties can however not be extracted separately.

At intermediate beam energies the situation for emulsion use is ideal. Almost all emitted particles stop in a normal stack and simple blob density measurements are sufficient to achieve a good charge identification of all tracks, except the very shortest where other methods are applicable (paper V). Since all the intermediate energy data in papers I, III, IV, V were recorded in the same stack, the calibration curves are very well determined.

One difficulty with the use of emulsion at these energies is the spread in beam energies over the scanned residual range interval of the primaries. This difficulty is partly overcome, either by involving the energy spread in the model comparisons or by analysing the spectra of, for example projectile fragments in the projectile rest frame.

The problem with a mixed (H,C,N,O,Ag,Br) target is discussed in papers III and IV. In central collisions one can by choosing only collisions with the largest multiplicities exclude the component of light emulsion target nuclei (H,C,N O). This could not be done for peripheral collisions, but on the other hand, in the first approximation the breakup properties of the projectile spectator should not be dependent on the target nucleus.

The investigations presented here only use the emulsion detector for the type of measurements for which it is advantageous namely event by event studies with as much information dug out of each event

as possible. Today's models are not developed to predict multiparticle correlation characteristics. Thus, in this thesis the exclusive data are often parameterized in a phenomenological way. They are compared with the very simplest inclusive predictions of the model calculations in order to search for deviations in specific types of events although the agreement with inclusive calculations might be fair.

2.2 The counter experiments.

When the CERN SC was equipped with a heavy ion source to produce ^{12}C ions at 85A MeV, it was natural to continue the work at intermediate energies with other techniques that allowed measurements with good statistical accuracy and studies of the sub-threshold pion production in a quantitative way.

A large vacuum scattering chamber (fig. 1) was connected to the accelerator beam pipe. The chamber was designed to allow measurements of i) High energy light particles emitted at large angles. ii) Low energy particles with Si detectors placed inside the cylindrical part of the chamber on movable arms with remote control. iii) Projectile-like fragments in the forward direction at angles down to 2^{o} close to the beam. The target could be rotated and changed without breaking vacuum.

At 85A MeV bombarding energy, one has to be able to cover protons from a few MeV up to ~200 MeV in order to record the complete light particle spectrum. ΔE-E techniques, in which the particle is stopped require much stopping material. Nuclear reactions in the detector material then become a considerable source of error for the most

energetic particles. The telescope for light particles (LPT in fig.2) used a transmission Si detector and plastic scintillators together with a time of flight measurement for the highest energies. The time of flight was used for particle resolution and double check of the energy calibration of the light output from the scintillators. The relatively large uncertainty (±10 MeV) for the highest energies is introduced by the calibration, based on the Si ΔE signals. Better energy resolution (for the plastic scintillators) would have been achieved with integrating ADC´s instead of the pulse height sensitive ADC´s which were chosen (for the Si detector).

The telescope designed for low energy light particles (the Si telescope in fig.2), was placed inside the vacuum chamber. The resolution is illustrated for a typical ΔE - E correlation in fig. 2. The Si detectors are easily calibrated. The ΔE and E values for the turning and crossing points (marked in the correlation plot) are calculable with the range-energy relation. The calibration can be checked in the off-line analysis, at any time during the experiment.

The π^+ telescope was a plastic scintillator range telescope. The short pulse length from plastic scintillators is advantageous for the detection of the μ^+ coming from the π^+ decay (time constant 26ns). The resolution for singly charged particles is demonstrated in fig. 3. The number of protons in the plot is reduced by about three orders of magnitude due to the required detection of a delayed particle. A typical spectrum for the time between the prompt and delayed pulses is also shown. It has the proper exponential shape and the correct time constant. The π^+ experiment has lately been repeated with 4 telescopes of this type but sliced into more segments, i.e. narrower energy bins /6/.

A proton spectrum at 90° was taken with one of these range telescopes for the reaction $^{12}C + ^{12}C$. The spectrum obtained overlaps with that from paper VI at energies $E_p > 80$ MeV. The test verifies both the slope and absolute level of the proton spectra from paper VI in this energy region. It should be noticed that no energy calibration is made of the range telescopes. The evaluation of the energies is only built on the range-energy relation. Consequently each scintillator constitutes one energy bin.

The off-line analysis has been done in Lund. The particle separation is based on the $\Delta E - E$ correlations which are displayed on a high resolution Tektronix 4015 graphical terminal screen. Normally the separation between different light particle isotopes is unambiguous and the two-dimensional identification constraints on the ΔE and E signals can be introduced via the terminal graphical input.

3. Summary of the publications.

Paper I.

Pion and proton multiplicities in heavy ion reactions at 75 - 200 MeV/nucleon.

R. Kullberg, A. Oskarsson and I Otterlund.
Phys. Rev. Lett. 40, 289 (1978).

This paper represents one of the first studies of heavy ion interactions at around 100A MeV bombarding energy. The experiment used the Bevalac 250A MeV ^{16}O beam on the emulsion target. Events in two energy ranges were selected 75A - 100A and 150A - 200A MeV. The production of charged pions was studied through ΔE - range measurements and examination of the track endpoints in order to find the characteristic pion decay products.

No measureable cross-section is observed for the production of charged pions. This is in sharp contrast to a result published prior to this one /7/. In that paper the authors claimed that the cross-section for charged pions was of the order of a few barns. It is shown in our paper that many protons are emitted with energy far above the beam energy per nucleon. We show that the huge cross-section reported could be understood if such fast protons erroneously have been identified as pions.

Our result was confirmed at the same time by another Berkeley experiment /8/. Recent quantitative studies with counter telescopes (see paper VII) verify that the integrated cross-section for π^+ is in

the range of a few tens of μb. Such small cross-sections cannot be measured in emulsion. 10 μb corresponds to 1 particle per 100000 events, an amount which is completely unrealistic to measure.

Paper II.

Properties of participants and spectators in non-peripheral Fe-induced reactions at 1.7A GeV.

K.B. Bhalla, S. Hertzman, B. Jakobsson, A. Oskarsson and I. Otterlund.
Phys. Lett. 82B, 216 (1979).

^{56}Fe has until recently been the heaviest nucleus accelerated to relativistic energies at the Bevalac. As the intensity so far has been low, emulsion experiments have been dominant. In this investigation central collisions were selected through constraints on the total charged particle multiplicity. The small number of slow particles in central collisions with the C, N, O target components was used to distinguish them from central Ag, Br events. The emission angles of all charged particles were measured.

In collisions between ^{56}Fe and light emulsion nuclei, the projectile is larger than the target. Thus also in a central collision there must, if the spectator-participant picture is taken literally always be a sizeable (nucleon number 20-30) projectile spectator left. We observe no projectile-like fragments with $Z>3$ in these events.

Data are compared with a calculation, where the participant is

treated with the fireball model /9/ and the spectator breakup is a pure spectator fragmentation /1/. Due to the different velocities of the participant and the projectile spectator, a double humped structure of the angular distribution should appear. This is not seen. Instead the emission at very forward angles, i.e. where the fragmentation particles should emerge, is supressed. The conclusion is that in these events, where the overlap between the nuclei is large, the spectator breakup is influenced by the participant processes. This causes either a smaller spectator than defined by the geometric overlap or an increased excitation of the spectator. This is reflected in the larger emission angles. Similar effects are seen in papers III and IV, when examining particle multiplicities and beam energy dependencies.

The fireball calculation can reproduce the large angle part ($\Theta > 10^{o}$) of the spectra fairly well. For ^{56}Fe + Ag, Br collisions, however, an excess of particles at 90^{o} is observed, which could be a signature of the hydrodynamical sidewards flow lately proposed /10/.

The following two papers concern ^{16}O induced reactions at three different energies: 75A, 175A and 2000A MeV. Projectile-like fragments with $Z \geq 2$ were identified, their emission angles measured and at 75A and 175A MeV their energy determined (if stopping). A separation of particles emitted from the projectile from those originating from the target nucleus was made. The breakup characteristics of the projectile (i.e. the degree of destruction and the momenta of the emitted fragments) were studied in each event and were correlated to the multiplicity of charged particles, emitted from the target.

Paper III.

The breakup of ^{16}O into He: an event-by-event study of nucleus-nucleus collisions at 75, 175 and 2000 MeV/A.

C. Bjarle, N-Y. Herrström, R. Kullberg, A. Oskarsson and I. Otterlund.

Nucl. Phys. A381, 544 (1982).

This experiment concentrates on events in which the ^{16}O projectile fragments into one or more He nuclei. The probability for multiple He fragmentation is large, probably as a result of the alpha particle substructure of the ^{16}O nucleus. The percentage of collisions with many He fragments is larger at 75A than at 2000A MeV. This means that at a certain impact parameter, the projectile spectator gets more excited, the higher the beam energy is (cf. paper II and IV).

Angular distributions of He nuclei from the projectile are built up of quite different contributions, depending on the He multiplicity in the event. In 4*He events the emission angles are much smaller than in events where only one He nucleus is the largest remnant of the projectile. This could again be a consequence of the intranuclear correlations in the ^{16}O nucleus.

The average target multiplicity <NT> is lower in 3 and 4*He events. For these, <NT> is independent of beam energy. Contrarily, in 1*He events <NT> is strongly increasing with bombarding energy. The interpretation must be that 3 and 4*He events are more peripheral

than those with small He multiplicities. For heavy nuclei the opposite has been observed /11/, i.e. a large He multiplicity is associated with central collisions.

Also the average emission angles of He, emitted from the projectile, are correlated to the degree of breakup of the target (<Θ> increasing with <NT>). At 75A MeV, where fragment energies could be measured, the average velocity of He fragments is considerably lower than that of the projectile, also for the most peripheral collisions. This retardation is much larger than corresponding shifts observed at 2.1A GeV /1/. The velocity shift increases with the destruction of the target.

Paper IV.

Correlations between projectile and target breakup in intermediate and high energy heavy ion collisions.

N-Y. Herrström, R. Kullberg, A. Oskarsson and I. Otterlund.
Nucl. Phys. A392, 474 (1983).

This paper presents a parallel analysis to that in paper III, but for all breakup channels of the projectile. A parameter (Q) is introduced as a measure of the disturbance of the projectile spectator. Q is defined as the sum of all charges carried away by multiply charged projectile fragments (which are all unambiguously identified). It is unlikely that the charges, which contribute to Q, have passed through the target nucleus. In paper III it was shown that events where the projectile breaks up into three or four He fragments are the most

gentle ones. Thus, for instance, a collision resulting in a ^{12}C fragment is believed not to differ much from an event with 3*He fragments. This is in fact seen in the NT-distributions which are identical for the different contributions to a certain Q-value.

Large Q values are then found in peripheral collisions. The probability for even Q-values is larger than for neighbouring odd ones, as a result of the preferred He channel.

The percentage of events with complete destruction of the projectile is much larger at 2000A MeV than at lower energies, in fact much larger than the fraction of completely overlapping collisions. Thus there must exist a mechanism which transports energy to the peripheral parts of the nuclei, increasingly efficient with beam energy even though the interaction time becomes shorter. A suggestion is that this is caused by the fast pions, which are produced in large numbers in the participant at 2000A MeV. Consequently, a certain excitation of the spectator occurs at a larger impact parameter at 2000A MeV compared to intermediate energies.

The average target multiplicity <NT> increases for smaller values of Q. The increase is stronger, the higher the beam energy is. This means that, at a certain excitation of the projectile spectator, the accompanying destruction of the target spectator is more violent at 2000A MeV, although the impact parameter is larger at this energy.

An important fact is that, at 75A MeV, the multiplicity of particles emitted from the projectile is the same as the corresponding target multiplicity, although the average target is a much larger nucleus (A = 59) than the projectile. This could mean that equal parts of the

projectile and target are participating in the reaction, also in central collisions. It is shown in paper V, that some of the particles emitted from the Ag or Br nuclei in central collisions have charges between 2 and 8. Thus, more charges are emitted from the target than from the projectile, although the number of particles was the same. Other indications, from inclusive nucleon spectra at intermediate energies, exist (see e.g. paper VI or ref 12,13) which imply that there is a hot source moving with half the beam velocity. Both its temperature and velocity are consistent with the equal participation idea.

The large shift in parallel velocity compared to that of the projectile, seen for He nuclei at 75A MeV is also there for heavier fragments. The shift at 175A MeV is quite consistent with 2.1A GeV data /1/, i.e. much smaller than at the lowest energy. The average transverse momenta of all types of projectile fragments are largest at 75A MeV, possibly due to the increased importance of the Coulomb deflection /14/. Both the shift of the parallel velocity and the transverse momentum at 75A MeV are increasing with the target destruction.

The type of results reported in papers III and IV cannot be fully understood in terms of the fragmentation model /1/, which succesfully explained the inclusive data. One basic assumption of the model is obviously violated in our results. The fragmentation of the projectile in peripheral collisions is assumed to be independent of the target nucleus, both its size and its mode of fragmentation. The fragmentation cross-section is said to factorize in one projectile and one target sensitive part. We have observed direct correlations between the projectile and target breakup in events which in an

inclusive experiment would have been called peripheral. Factorization is only applicable on the most peripheral collisions. The large parallel velocity shift at 75A MeV is not foreseen by the fragmentation model.

Paper V.

The disintegration of nuclei in violent heavy ion interactions at 55A MeV - 110A MeV.

B. Jakobsson, G. Jönsson, B. Lindkvist and A. Oskarsson.
Z. Physik A307, 293 (1982).

This study concentrates on central collisions at intermediate energies produced by the 250A MeV ^{12}C beam at the Bevalac. Only collisions which due to their large number of emitted charges, must be with Ag or Br target nuclei were analysed. The secondaries with $Z \leq 8$ were identified and all ranges (energies) and emission angles were measured. The charge of the residual target recoil was determined indirectly, by subtracting the sum of identified emitted charges from the total charge content of the projectile and target nuclei.

The events, selected by their multiplicity, have no projectile-like fragments in the forward direction (Q = 0 in the terminology of paper IV). Only about one singly charged particle per event is emitted in the projectile fragmentation region. Some events are seen, where several medium-charged fragments ($3 \leq Z \leq 8$) are emitted. Such multi-fragmentation events could not be understood in a simple thermal

picture.

Besides this component of fragments with $Z < 8$ a heavy recoil nucleus must exist in almost all events. The momentum transfer to that target recoil is considerably less than the full momentum transfer in a fusion reaction. The corresponding recoil velocity (~0.02c) is consistent with the average velocity of the low energy, target associated protons.

The parallel momentum spectra of light particles can be qualitatively explained in a three source thermal picture. The projectile source would then be very weak, while the intermediate and low velocity sources account for the majority of light particles, with about the same strength. A similar interpretation is made in connection with paper VI, where quantitative estimates of temperatures and source velocities are given. They are, however, for impact parameter averaged data.

We have also analysed the energy flux in the direction of the beam through a parameter ($q_{\parallel}$) describing the parallel energy fraction defined as the ratio between the parallel and total kinetic c.m. energy for all charged particles. We find, in spite of the large multiplicities selected, that the majority of the events have quite large $q_{\parallel}$ values, larger than 0.5, which is the natural value in a cascade process. Hydrodynamical behaviour would presumably lead to even lower values. So, also central collisions show some momentum transparency. It should be said that the $q_{\parallel}$ distribution is broad and some events are seen where only 30% of the energy is transferred in the forward direction.

Paper VI.

Proton emission in 58A and 86A MeV ^{12}C-induced heavy-ion reactions.

B. Jakobsson, L. Carlén, P. Kristiansson, J. Krumlinde, A. Oskarsson, I. Otterlund, B. Schröder, H-Å. Gustafsson, T. Johansson, H. Ryde, G. Tibell, J.P. Bondorf, G. Fai, A.O.T. Karvinen, O.B. Nielsen, M. Buenerd, J. Cole, D. Lebrun, J.M. Loiseaux, P. Martin, R. Ost, P. de Saintignon, C. Guet, E. Monnand, J. Mougey, H. Nifenecker, P. Perrin, J. Pinston, C. Ristori, F. Schussler.

Phys. Lett. 102B, 121 (1981).

The experiment, presented in this paper produced the first data on proton emission at large angles, at intermediate bombarding energies. The reactions studied were ^{12}C + C, Al, Cu, Ag, Au at 85A MeV and ^{12}C + Ag at 58A MeV. Angles from 30-140^{o} were covered. After publication of this paper an experimental mistake was discovered. This strongly affected the shape of the published spectra in the region 30-60 MeV. The paper is nevertheless included in the thesis since the error has only weak influences on some of the qualitative discussions in the paper and none at all on the derived quantitative numbers.

First I will explain the error, how it is corrected for and show the corrected spectra. At angles <55^{o}, the light particle telescope (LPT in fig. 2) included a long time-of-flight distance (2.2 m in a vacuum tube). To be recorded, a particle had to reach the plastic scintillator at the end of this tube. Thus the telescope was very sensitive to the direction of the particle. On its way from the target it passed 1 mm Si, 0.5 mm stainless steel windows and 1 mm

plastic start detector (the material which sets the lower detection limit). Multiple Coulomb scattering in this material deflected some of the slowest particles from the telescope axis. Therefore they never reached the stop detector and were consequently never recorded. This is the reason for the forward spectra showing a dramatic fall-off below 50 MeV.

The multiple Coulomb scattering is strongly dependent on the charge and momentum of the particle and can be corrected for by semi-empirical methods described in ref. 15. It turns out that the correction is as large as a factor of two for 30 MeV protons (remember that these particles have lower energy when passing through the scattering material). For 60 MeV protons the correction is negligible. At larger angles than 55^{o} a shorter flight path was used (0.5 m). Thus this telescope was less sensitive to the direction of the particle. There, the correction was only a few per cent.

In figs. 4 and 5 the corrected spectra are shown. The only changes of importance are in the region 30-60 MeV for angles $<55^{o}$. The correction method is uncertain for the lowest energies and not too much attention should be focused on the 30-40 MeV data. The pronounced peak has disappeared and looks more like a flat spectrum. The spectra are still very similar regardless of the target nucleus.

The parameterization done in the paper with a moving thermal Boltzmann source, has been checked for the corrected spectra. The temperatures (13-17 MeV) deduced from backward spectra are not sufficient to describe the flat slopes at $30-60^{o}$. Some contribution from a fast source, probably associated with the projectile is needed. It should be mentioned, that the shapes of backward spectra

are not very sensitive to the velocity of the intermediate source. Recent experiments /12.13/ also reach the conclusion that the hot source has about half the beam velocity both for light and heavy targets.

For the Au target, the low energy spectra of light particles were measured with a Si-telescope (fig.2). Complete proton spectra are presented in fig. 5. The absolute normalization of the data taken with the Si-telescope ($E < 25$ MeV) is uncertain by ±30% compared to the higher energies. The smooth matching at backward angle is nevertheless satisfactory. The cross-section describes a peak at all angles showing typical characteristics of an evaporation spectrum from a residual nucleus which moves slowly in the forward direction. Three sources are needed to reproduce the spectra of fig. 5. The projectile fragmentation source contributes only weakly at these large angles. The intermediate velocity Boltzmann source has a temperature T=19 MeV, somewhat larger than the value obtained in the paper (determined by backward angles). The low energy part is then described by an evaporation of protons from a target residue with β=0.03c and T=5 MeV. In this fit the Coulomb repulsion has been accounted for. This does not change the temperature deduced for the intermediate source considerably.

It is difficult to estimate how accurate the temperatures, obtained for the hot source in the fitting procedure, are. The admixture from different sources is difficult to handle properly. Including the experimental uncertainties, a reasonable guess would be about ±2 MeV. The temperatures weakly increase with the target mass. Thus the ratio between the contributions from the projectile and target, to the hot source, cannot decrease with the target mass, as expected

from any participant formation of the overlap volumes. Together with the observed similarities for different targets the implication is that the reaction takes place between equal parts of the projectile and the target.

The fact that the thermal model does provide a reasonable description of the data, does not necessarily mean a proof of its validity. Also a nucleon-nucleon scattering cascade calculation would presumably give similar results. Most probably the real situation is a mixture of the two processes. The contributions are then determined by the sizes of the nuclei and the actual impact parameter.

Paper VII.

Sub-threshold pion production in heavy-ion collisions at 85A MeV.

T. Johansson, H-Å. Gustafsson, B. Jakobsson, P. Kristiansson, B. Norén, A. Oskarsson, L. Carlén, I. Otterlund, H. Ryde, J. Julien, C. Guet, R. Bertholet, M. Maurel, H. Nifenecker, P. Perrin, F. Schussler, G. Tibell, M. Buenerd, J.M. Loiseaux, P. Martin, J.P. Bondorf, O.B. Nielsen, A.O.T. Karvinen and J. Mougey.
Phys. Rev. Lett. 48, 732 (1982).

In the last paper the sub-threshold pion production is returned to, with the aim to make quantitative measurements of π^+ production cross-sections. Two experiments have been done, the first presented in paper VII, and the other recently completed /6/. The last one confirms and completes the data of the first experiment. The telescope is schematically shown in fig. 3.

The CERN SC ^{12}C beam was run at 85A and 75A MeV. π^+ production on light (^{7}Li and ^{12}C) and heavy (^{208}Pb and ^{197}Au) targets was studied. The double differential invariant cross-sections of π^+, plotted in figs. 6 and 7, are from the latest experiment. Obviously the first measurement is completely confirmed. The cross-section falls by about a factor of 3-4 between 85A and 75A MeV for the reaction $^{12}C + ^{12}C$ at the studied angles. The conclusions drawn from figures 6,7 are basically the same as those of paper VII.

The absolute levels of the spectra are quite consistent with a nucleon-nucleon scattering calculation /16/, where the Fermi-momenta of the nucleons are included. The Pauli blocking and the reabsorption of pions on their way out through the nuclei must also be included. Otherwise, the calculated cross-sections will be far above the measured data.

We have analysed the angular distributions in the nucleon-nucleon c.m. frame. For $^{12}C + ^{12}C$ the emission is quite symmetric although not isotropic but forward - backward peaked. For the heavy targets (^{208}Pb and ^{197}Au) the spectra are backward peaked while for ^{7}Li target the forward emission is favoured (refers to the nucleon-nucleon system). It is at the moment not quite clear whether this is in contradiction to the nucleon - nucleon scattering approach. The added effects of Pauli-blocking and reabsorption might perhaps produce the observed skewness in asymmetric reactions.

4. Remarks.

The phenomena we are about to study in nuclear collisions at energies per nucleon far above the nuclear binding energy show extreme complexity, due to the large number of emitted particles. In the most sophisticated experimental setup we can think of today (e.g. the Plastic Ball) one cannot expect to detect all of these particles (to measure the neutrons would be a formidable task). Thus we have still too many unknowns to be able to make the ideal event by event experiment.

Moreover, we expect quite different things to happen depending on the specific input parameters (the sizes of the nuclei and the impact parameter). With small projectiles (until now the only ones available) and targets it is very unlikely that one produces a thermalized system (it takes a nucleon about 3 collisions to reach equilibrium). Similarily, large impact parameter collisions should show a strong knock-on contribution. Only in central collisions, presumably between heavy nuclei, should the hydrodynamical and collective effects be enriched.

Unfortunately we have no distinct measure of the impact parameter in a model independent way. Thus the inclusive measurements done have not been able to clarify the situation. Most models can describe certain aspects of data, but none of them manages at the same time (with a fixed set of parameters) to explain both nucleon spectra, composite formation and pion production.

Thus far the discussion concerns the shapes of inclusive spectra Absolute calculations are often good to within about a factor of two.

This resemblance with data is often claimed to be a satisfactory result. Correct within a factor of two is in fact not too impressive as far as nucleon spectra goes. The conservation of charge for a light system say $^{12}C + ^{12}C$, limits the possible range of the cross-section to one order of magnitude if the reaction cross-section is known. It is also an embarrassing fact that experimentalists cannot measure absolute cross-sections to better than ±20-30%. Considerable improvement must be made on this point.

Procedures (like the one used in paper VI) to describe inclusive spectra with 3 moving thermal sources are not very conclusive. Of course they can fit data, with 9 free parameters (the temperature, the velocity and the number of particles emitted from each source) what else could you expect. Such models are useful to parameterize data, but their predictive power is indeed of limited value.

The richness of 4π data is encouraging. The competition to emulsion experiments has indeed so far not been very hard. Of course, emulsion experiments suffer from the poor statistical accuracy, but are anyhow quite conclusive. They can in fact provide useful hints for the experimental work in the near future.

The event information contained in the Q parameter introduced in paper IV is very useful. An experimental set-up with a counter hodoscope covering the forward fragmentation cone can integrate the energy of projectile particles, which have not interacted directly with target nucleons (this would be even better than simply to count the charges). If one could include also the energy carried away by fast neutrons, the input channel of each event could be determined i.e. how many nucleons participate and how much energy has been

released in the process. This information is even more straightforward than a measure of the impact parameter and should provide a way to determine the correspondence between the "phenomenological" temperature and the excitation of the system.

In paper V the parallel energy fraction was determined for each event. Other parameters which involve the added properties of all registered particles are Thrust and Sphericity /17/. Both properties can be extracted from emulsion experiments at intermediate energies. For this type of analysis, the missing neutrons are problematic. These have to be accounted for in the model calculations.

The emulsion detector will have its applicability in certain areas although the competition from the Plastic-Ball and Streamer Chamber experiments will be tough. An experiment which could immediately be done in emulsion concerns the multifragmentation of large nuclei (paper V). Such phenomena are easiest to study in the projectile rest frame. Thus, experiments should be done with the very heavy projectiles Xe , Kr and even Au and U now (spring 83) available at the Bevalac. With these large projectiles, accelerated to ~1A GeV, hundreds of charged particles might be emitted in an event. The emulsion detector is outstanding in handling such large multiplicities.

It has often been pointed out /18/ that the inclusive measurements done, cover only a limited part of the available phase-space and that one should proceed to low cross-section phenomena. The subthreshold pion production (paper VII) is an example of this. Further studies of subthreshold pion production should involve simple coincidence experiments, although difficulties arise due to the low

cross-section. Coincidence measurements between the pion and the accompanying nucleons can shed light on the nucleon-nucleon scattering contribution. Perhaps the preference for the deuteron channel can be seen /16/. Pion - projectile fragment correlations can tell whether the pion producing events are peripheral or central. This is essential for the treatment of pion reabsorption. The Coulomb force, affects the charged pion spectra strongly at these energies /6/. After a normal Coulomb correction has been applied to the measured π^+ and π^- spectra, these show a large excess of π^-. in the case of a very heavy target. In fact the excess is much larger than expected from the N/Z ratio of the ^{208}Pb target. This has to be studied with a technique more suitable for π^- detection. presumably a magnetic spectrometer. Tracing the pion production down with beam energy, is probably easiest to do with π^o. Promising results have been presented lately by Grosse et. al.

In this last section I have expressed some ambitions that one could have for future experiments. The selection of possible experiments are in the line of the work done in this thesis. They are not at all wild unrealistic dreams but perfectly feasible with today's technology.

I would like to end with some personal reflections about this field of physics, which has taken the best years of my life (perhaps it made them the best (so far)). My feelings are coloured by the excitement of working in totally unexplored domains where there are still possibilities to touch exotism (although it has not been done yet) even by accident.

It is inherent in these many-particle problems that the observables

measured are averages over many different interaction channels and must be described by statistical methods. Such models can provide a convenient strategy, attacking the microscopic properties which must be the ultimate goal for our search. The models themselves are unfortunately neither very exciting nor beautiful. Anyhow they have the advantage of being easy to visualize with classical analogies.

The great experimental efforts, both new accelerators and large detection systems in the very near future must be matched by theoretical activities, in order not only to fit existing data in a more or less phenomenological way but also to produce predictive models, which can tell for what and where to search.

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Other references of interest appear in papers I - VII.

Figure captions.

1. The scattering chamber viewed from above. The square boxes in front can be removed to reach larger forward angles.

2. Simplified drawings of the telescopes used for light particle spectra. An example of the particle resolution for the low energy telescope is presented. The points marked by arrows were used for calibration.

3. The plastic scintillator range telescope used in the first experiment. The correlation plot shows the singly charged particles, after a strong hardware rejection of p and d. The time spectrum is obtained after further restrictions on the ΔE and E signals.

4. The proton energy spectra for several targets after the correction for multiple scattering.

5. Corrected proton energy spectra for Au target. The low energy part was measured separately. There is an uncertainty in the absolute level between the low and high energy distributions of about ±30%.

6. Invariant π^+ cross-sections at 85A and 75A MeV. The guide lines connect the data points from the recent experiment. The results from the first experiment (paper VII) are included for comparisons (open circles).

7. The same as for fig. 6 but for Li and Pb target at 85A MeV only.

The Vacuum Scattering Chamber.

The figure shows the chamber in the experimental zone. The fragment- and light particle telescopes are placed at typical angles. The concrete walls limit the flight path in LPT at angles larger than 55^{o}.

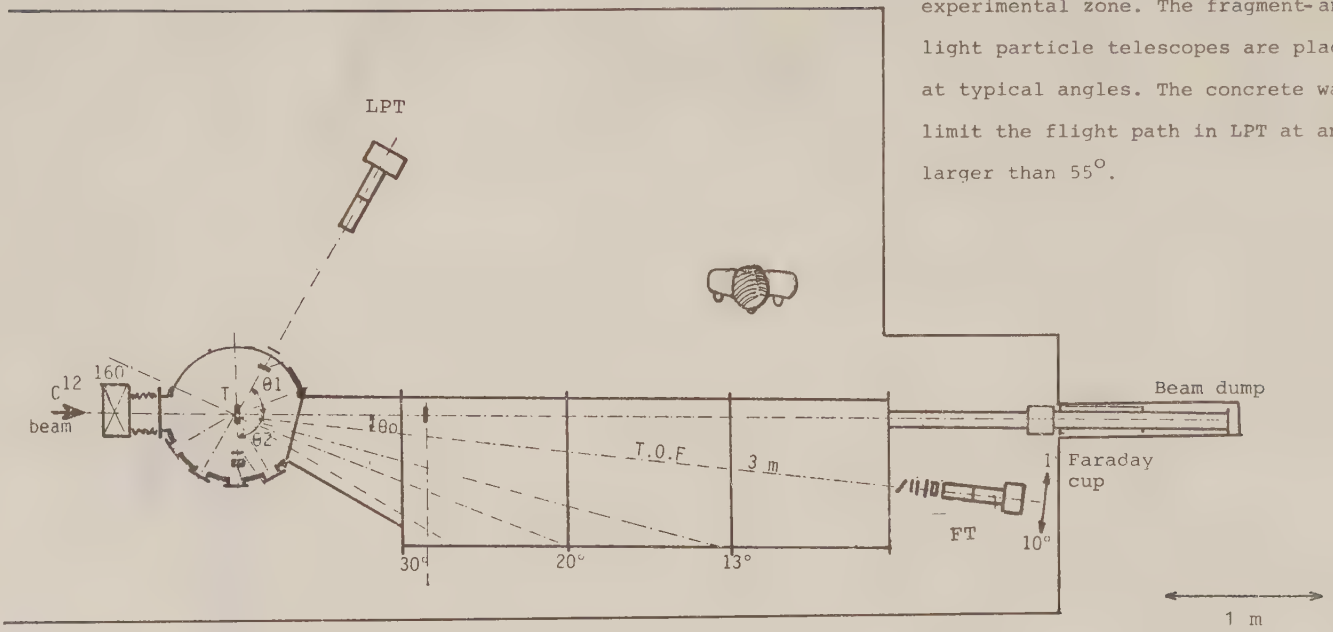
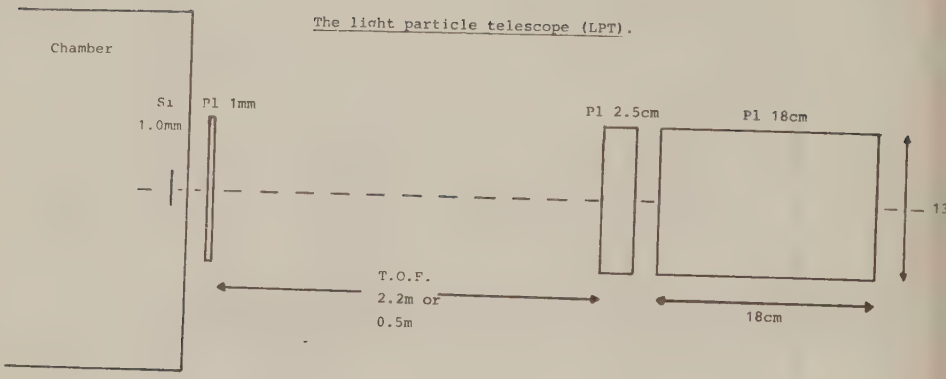
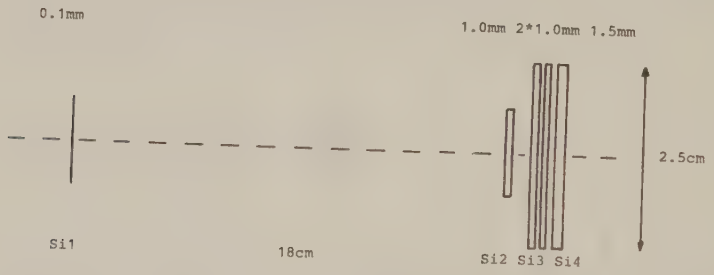


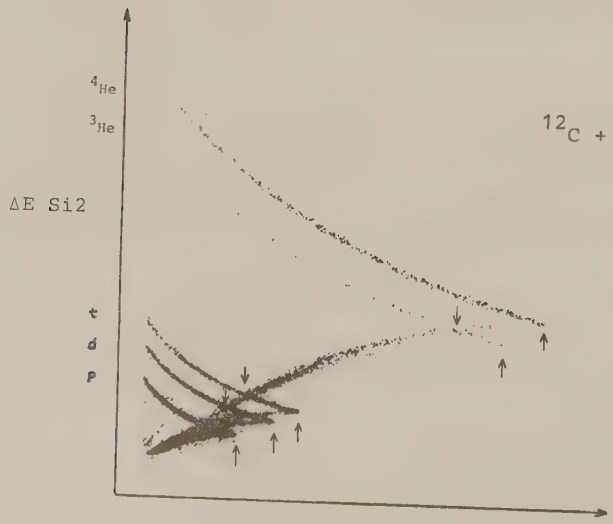
Fig. 1



The Si telescope, inside chamber.

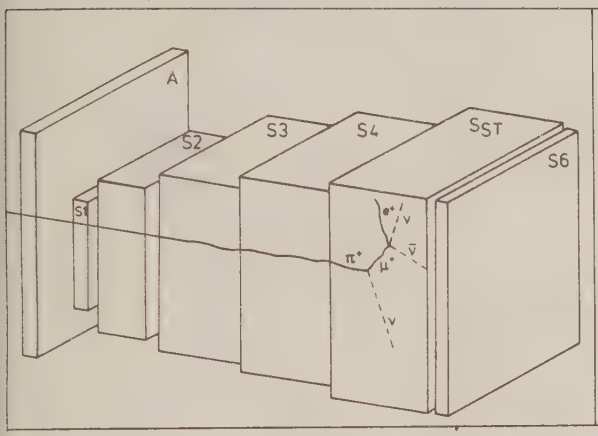


The Si3 signal is added from 2 1mm detectors.



$^{12}C + Au \rightarrow p,d,t,^3He,^4He$

Fig. 2



TELESCOPE - DATA

	Thickness (mm)	Area (cm^2)	E_{mean} (MeV)	ΔE (MeV)
A	8			
S1	5	6×6		
S2	25	8×8	23.7	13.2
S3	50	9×9	39.6	18.5
S4	50	10×10	56.5	15.4
S5	50	11×11	71.3	14.2
S6	5	11×11		

$^{12}C + {}^{12}C \rightarrow \pi^+$ at 86A MeV
Lab. angle 90°

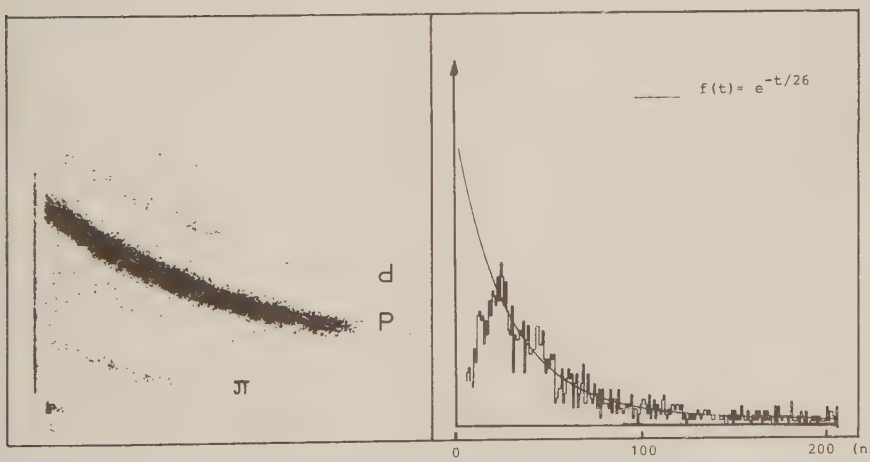


Fig. 3

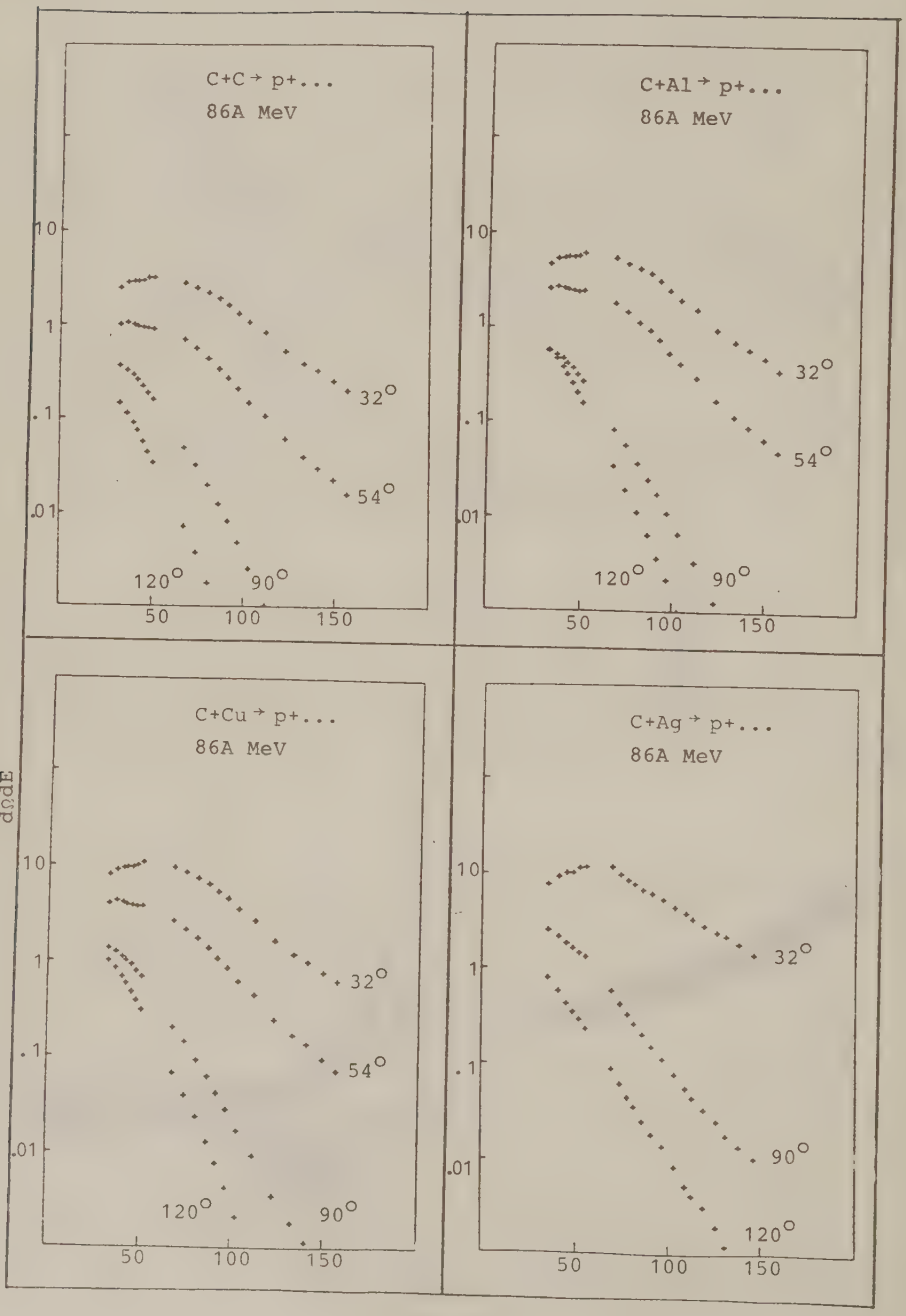

C+C → p+...
86A MeV
C+Al → p+...
86A MeV
C+Cu → p+...
86A MeV
C+Ag → p+...
86A MeV
32°
54°
90°
120°
10
1
.1
.01
50
100
150
$\frac{d^2\sigma}{d\Omega dE}$ (mb/Sr MeV)
E_p (MeV)

Fig. 4

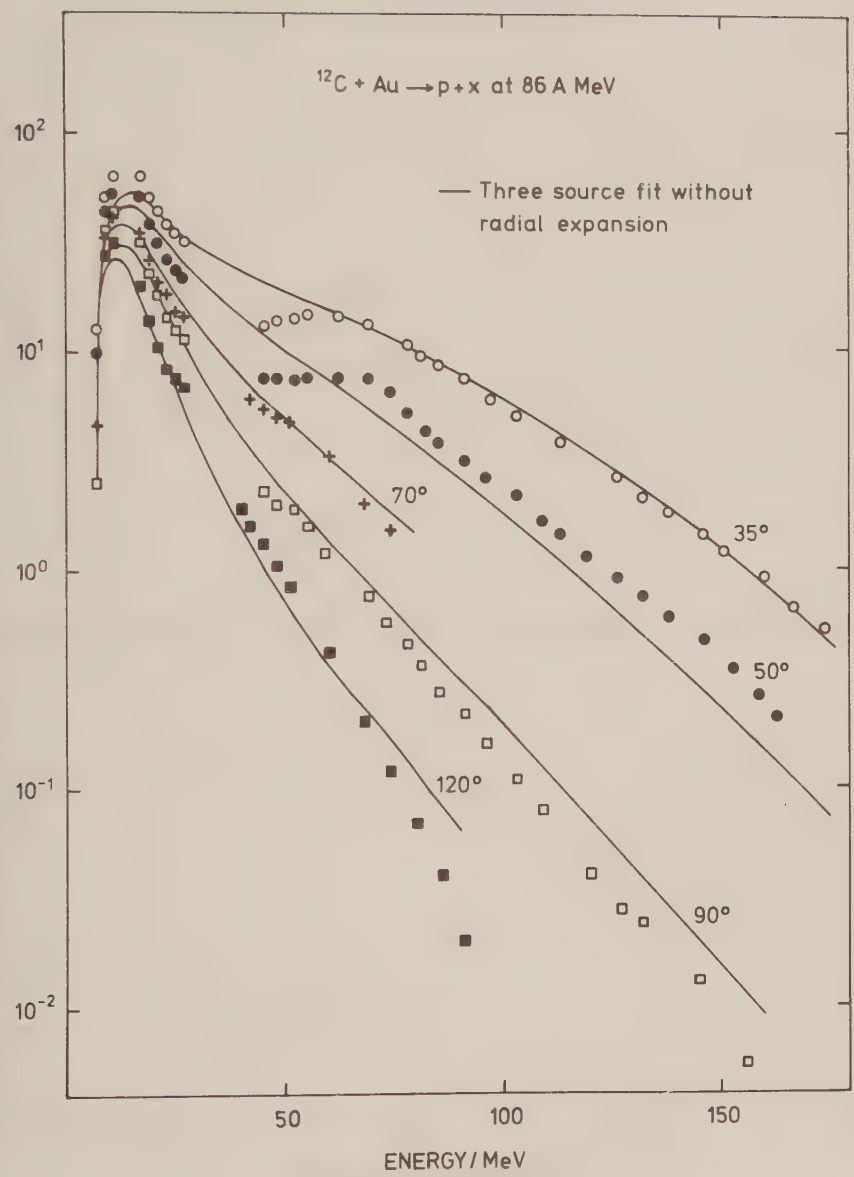

$^{12}C + Au \rightarrow p + x$ at 86 A MeV
Three source fit without radial expansion
35°
50°
70°
90°
120°
10^2
10^1
10^0
10^{-1}
10^{-2}
50
100
150
ENERGY / MeV
$\frac{d^2\sigma}{d\Omega dE}$ / (mb / sr MeV)

Fig. 5

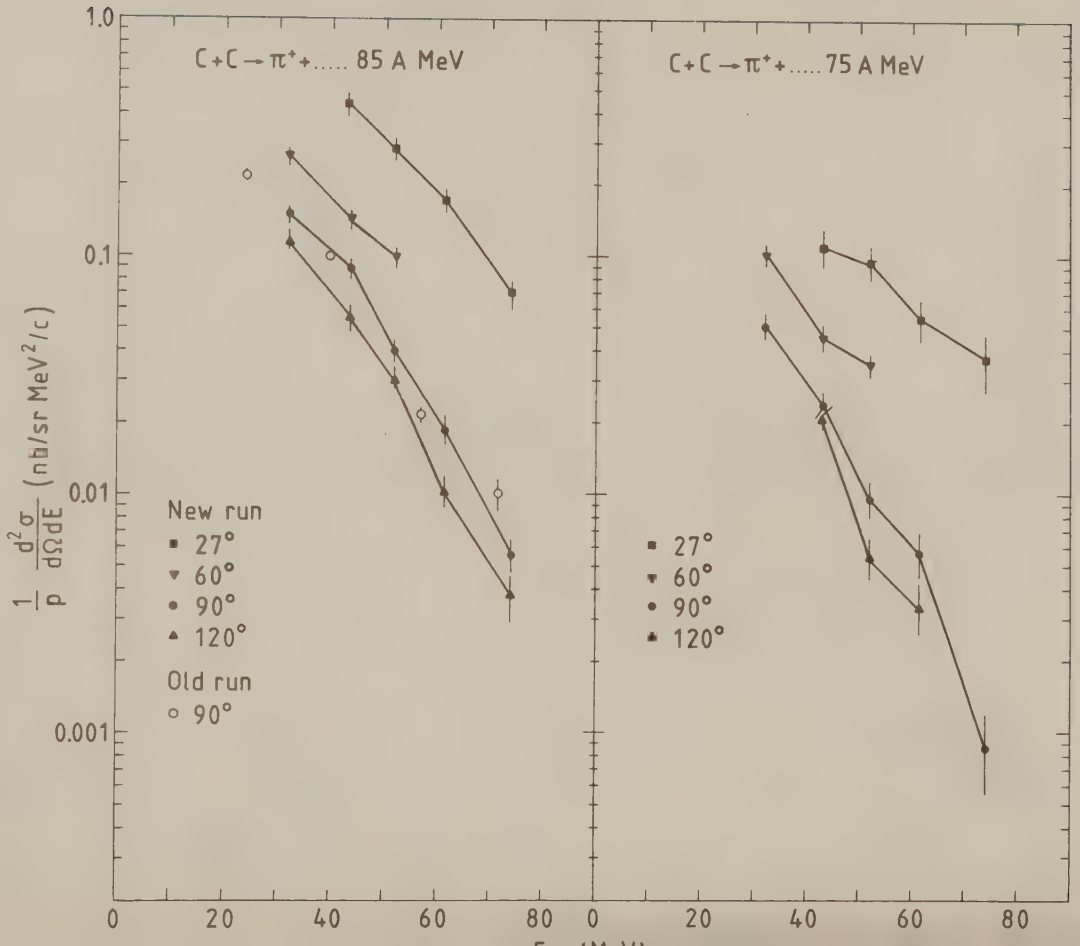

C+C → π⁺+..... 85 A MeV
C+C → π⁺+..... 75 A MeV
New run
27°
60°
90°
120°
Old run
90°
27°
60°
90°
120°
1.0
0.1
0.01
0.001
0
20
40
60
80
$\frac{1}{p}\frac{d^2\sigma}{d\Omega dE}$ (nb/sr MeV²/c)

Fig. 6

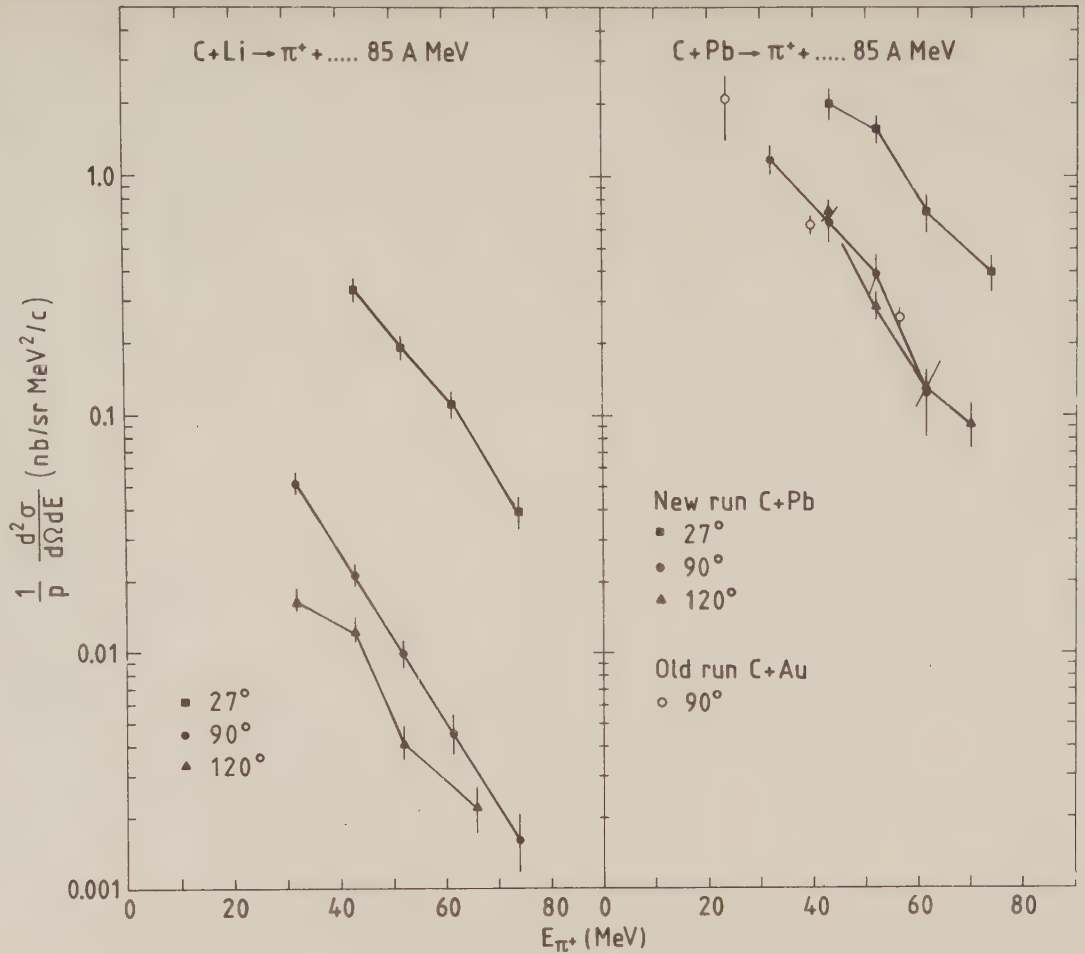

C+Li → π⁺+..... 85 A MeV
C+Pb → π⁺+..... 85 A MeV
1.0
0.1
0.01
0.001
0
20
40
60
80
$\frac{1}{p}\frac{d^2\sigma}{d\Omega dE}$ (nb/sr MeV²/c)
E_{π^+} (MeV)
27°
90°
120°
New run C+Pb
27°
90°
120°
Old run C+Au
90°

Fig. 7